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An evaluation system based on the self-organizing system framework of smart cities: A case study of smart transportation systems in China

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ABSTRACT

Smart cities have been developing aggressively around the globe, especially in China. As of 2017, more than 1000 cities in the world have commenced smart city developments, half of which are in China. However, there is not a uniform and clear understanding of smart city systems; this may affect their evaluation/planning and lead to misguided construction. Smart cities are characterized by complex self-organizing systems, and thus their sustainable and healthy development may require following the evolutionary patterns of such systems. Hence, self-organizing system theory may be useful in explaining such cities. Therefore, this paper first performs secondary qualitative data analyses of previous attempts at characterizing smart city development to identify the most robust aspects tested in previous work. Then, incorporating the results, self-organization theory is used to develop an overall, comprehensive system framework of smart cities. In this framework, all types of smart devices are the basic units of development (defined as "smart cells"). Meanwhile, Information and Communications Technology (ICT) and developmental mechanisms offer technical support and regulatory mechanisms in the spontaneous operation of smart cities. These three dimensions (smart cells, ICT, and developmental mechanisms) are combined into a scalable and distributed smart city evaluation system. Finally, smart transportation systems and the current state of these in China are used as a case study for discussion.

1. Introduction

At present, more than 50% of the human population lives in cities around the world. The United Nations Development Program predicts that by 2030 cities will accommodate two-thirds of the global population, which means that cities of the future will be increasingly populated and urban issues will also become exacerbated. Smart cities provide feasible solutions to urban issues such as environmental pollution, scarcity of resources, traffic congestion, and public safety. The concept of smart cities, which originated from the New Urbanism and Smart Growth Movements in the late-1900s, aims to solve various issues caused by urban development (Burchell et al., 2000; Calthorpe, 1993; Chang et al., 2018). Following the 2008 financial crisis, which led to a global economic recession, Europe and America took on a pioneering role in developing smart cities as a new means to drive economic growth. In 2010, the smart city concept was introduced in China. As of 2017, more than 1000 cities in the world have implemented smart city development, half of which are Chinese cities, while issues such as overdevelopment and wanton development have become more obvious. As smart cities require long construction periods and huge investments, an efficient pre-planning evaluation system is essential to ensure the healthy development of smart cities, especially in China.

To this end, it is necessary to first define the system framework of smart cities before constructing a dynamic and rational evaluation system based on that definition. If not, evaluation systems will inevitably be incomplete and inconsistent. For example, some previous evaluation systems evaluate 'quality of life' as a dimension (Mahizhnan, 1999; Thuzar, 2012); however, quality of life may not represent an independent dimension of a smart city, as all the initiatives in a smart city ultimately aim to raise the quality of life (Shapiro, 2006). The lack of a complete smart city framework could also lead to important dimensions being excluded from evaluation systems. According to current research (Hall et al., 2000; Lee et al., 2013; Mohanty et al., 2016; Odendaal, 2003), the concept of a smart city, which is a multi-faceted one, is supported by the Internet of Things (IoT), cloud computing, remote sensing (RS), geographic information systems (GIS), and global positioning system (GPS) technologies. It is a city that has attained an advanced form of urban informatization as a successor of digital cities

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and intelligent cities, and it can be viewed as an ecosystem formed by subsystems that include humans, matter, transportation, energy, business, and communication, deeply integrating the components of informatization, industrialization, and urbanization. Discussions on the system framework of smart cities mainly focus on technical support and urban development, relying on the traditional and neoclassical theories of urban growth and development (Albino et al., 2015). Researchers have attempted to define a universal smart city architecture to facilitate real-world deployment of smart cities. However, this has proven very difficult (Silva et al., 2018; Vijayakumar et al., 2018). This is not only a research gap in this academic field, but it also affects the development outcomes of smart cities, an urgent problem to address at present. Even more, we have become accustomed to the idea of an administrative body planning and controlling urban development, with the loss of control as a hovering source of fear. Nevertheless, it seems daunting to plan an entire city, and the role planners may play in future urban development is becoming increasingly uncertain (Juval, 2000). Juval (2000) introduced the idea that cities maybe self-organizing systems, emphasizing that the open, nonlinear, fluctuating, and non-equilibrium nature of urban systems, as well as the synergetic, competitive, chaotic, orderly, and self-similar mechanisms of their development and evolution, are in line with the characteristics of self-organizing systems. Barthelemy et al. (2013) claimed that centralized, top-down planning and interventions seriously restrict the dynamic development of cities. Taking these two notions into consideration, self-organizing system theory may be highly useful in explaining the development of cities, particularly smart cities. While some papers incorporate self-organizing system theory to discuss smart city systems, they mainly focus on the technological aspect (Cia et al., 2018; Lu et al., 2015; Qureshi et al., 2017; Sharma et al., 2018) or on a specific component, such as the transport system (Hercog, 2004; Sanchez-Iborra and Cano, 2017).

However, Albino et al. (2015) argued that it is too difficult to create an all-inclusive system for assessing smart cities and that an evaluation system should be tailored to a particular city's vision. Indeed, a review (in the present study) of previous evaluation systems seems to support this view. However, these previous systems are mainly based on the traditional and neoclassical theories of urban growth and development, and we believe that both all-inclusive and tailored evaluation systems can be constructed. This paper employs self-organization theory, especially the cellular automata (CA) model (which utilizes two main factors: cells and rules), to comprehensively analyze the potential components of an overall system framework of smart cities. Based on the results, it proposes a scalable and distributed smart city evaluation system comprising three dimensions for the development of smart cities: "smart cells" (smart devices, as the basic units of development), Information and Communications Technology (ICT), and developmental mechanisms. Finally, it tests the framework, and analyzes the role of humans in the evolution of self-organizing smart city systems, through an in-depth analysis of smart transportation systems as a case study.

This paper provides unique findings and contributions. First, the framework represents a concise and unified evaluation system covering all aspects of smart city systems. Second, it allows one to focus on a particular city or subsystem of a smart city and still obtain satisfactory evaluation results. This is achieved by evaluating specific smart cells, which reflects the scalability and adaptability of the evaluation system. Third, we emphasize the vital core role of various types of smart devices, or smart cells (see below), in the evolution and development of smart cities. This will encourage not only big enterprises like IBM but also many smaller companies to participate in the construction of smart cities. In this way, the construction of smart cities will play a greater role in promoting economic growth. In addition, our analysis approach has merits, making this paper innovative in a few ways. First, it departs from the "vertical" approach of many existing evaluation systems, which tend to demarcate smart city systems while neglecting the "horizontal" relationships among various system components. This is done by using self-organization theory to specify the horizontal and vertical relationships of the various system components to form a distributed smart city evaluation system. Second, smart city systems are analogized to the human body, whereby various types of smart devices are defined as "smart cells."

Overall, our results should serve as a guideline for the development of truly smart cities based on the robust framework presented herein. The remainder of this paper is organized as follows. The following section reviews urban self-organization theory and analyzes previous work on smart city evaluation systems, especially the "New Smart City Evaluation Index (2016)" jointly issued by the Standardization Administration of the People's Republic of China, Office of the Central Leading Group for Cyberspace Affairs and the National Development and Reform Commission. Section 3 briefly introduces the research methodology of this paper. Section 4 constructs self-organizing system structures of smart cities and refines smart city evaluation systems based on these structures. This is followed by a case study on smart transportation systems in Section 5. Finally, Section 6 summarizes conclusions and future work.

2. Literature review

2.1. Smart city evaluation systems

2.1.1. Evaluation system of the intelligent community forum

Established by the Telecommunications Industry Association in the United States, the Intelligent Community Forum (ICF) strengthens international cooperation by focusing its research on economic systems based on broadband construction. The ICF is also concerned with how to create job opportunities and promote economic development as well as discover new business models and implementation methods that are practical for daily application within such economic systems, so as to boost the competitiveness of these cities. The forum, which is a representative global smart city rating agency, has six primary indicators: Broadband, Knowledge Work, Innovation, Digital Inclusion, Marketing and Advocacy, and Theme of the Year. The first five indicators are further expanded into 18 secondary indicators, and the themes of recent years have been "Intelligent Medical Community," "Innovation Platform," "Innovation and Employment," "Power of Culture," and "Revolutionary City." As the first smart city evaluation system in the world, the ICF is primarily based on qualitative evaluations and the index weights are not specifically quantified. ICF believes that the key elements of successful smart city development are collaboration, cooperation, leadership, and sustainability (Miller et al., 2010).

2.1.2. Evaluation system of the European Union

In terms of smart city development, the European Union (EU) emphasizes the application of Information and Communications Technology (ICT) in areas such as urban ecosystems, transportation, healthcare, and intelligent architecture. The EU intends to achieve energy savings and carbon emissions reduction targets by knowledge sharing, so as to promote the sustainable development of low-carbon smart cities. In October 2007, the Centre of Regional Science (Vienna University of Technology, Austria), the University of Ljubljana in Slovenia, and the OTB Research Institute for Housing, Urban and Mobility Studies (Delft University of Technology, the Netherlands) formed an evaluation center that employs 6 primary indicators (Smart Economy, Smart People, Smart Governance, Smart Mobility, Smart Environment, and Smart Living), 31 secondary indicators, and 74 tertiary indicators to assess medium-sized cities in Europe (Giffinger et al., 2014). The indicators for each level are of equal weight. For example, the weights of the six primary indicators are 17%.

2.1.3. Evaluation system of China

In 2014, the Standardization Administration of China, the Office of the Central Leading Group for Cyberspace Affairs, and the National

Table 1
Evaluation system of the guidance document.
Data source: Guidance on the construction and application of the smart city standard system and evaluation index system. Retrieved from http://www.cnscn.com.cn/news/show-htm-itemid-16728.html

Type of indicators	Primary indicators	Secondary indicators
Function-oriented indicators	Information resources	Openness of information resources; sharing of information resources; development and utilization of information resources
	Network security	Network security management; monitoring, warning and emergency responses; safety and controllability of information systems; key data security
	Creativity	Application of new-generation information technologies; model innovations; technological R&D and innovations; transformation of scientific research achievements
	Developmental mechanisms	Planning and construction programs, standard system; policies and regulations, investment and financing mechanisms; organizational management mechanisms
Results-oriented indicators	Infrastructure	Information technology infrastructure; public infrastructure
	Public services	Convenience and Efficiency of Services; variety of services, coverage of services; integration of services; satisfaction levels of services
	Public administration	Processing speed; openness of administration; accuracy of administration; inter-department cooperation; public security administration standards; establishment standards of credit environment
	Livability	Degree of improvements to living environments; prevention and control capacities of environmental monitoring; standard of community information services; digitalization degree of lifestyles
	Industrial structure	Informatization standards of agricultural production and operations; integration standards of informatization and industrialization; capacity to provide new information services; e-commerce development and application outcomes

Development and Reform Commission jointly issued a document entitled "Guidance on the Construction and Application of the Smart City Standard System and Evaluation Index System" (hereafter referred to as the "guidance document"), which preliminarily proposed the system framework of smart cities. The evaluation system based on the said system framework comprises four function-oriented indicators (Information Resources, Network Security, Creativity, and Developmental mechanisms) and five results-oriented indicators (Infrastructure, Public Services, Public Administration, Livability, and Industrial Structure), as shown in Table 1 (National Development and Reform Commission, 2015). The guidance document states that the names of the primary indicators may be revised accordingly to reflect sector-based characteristics. For example, the "Public Services" primary indicator could be amended as "Medical Services" to be a corresponding primary indicator within the smart medical sector. The secondary indicators comprise core indicators and expanded indicators, whereby the former are compulsory indicators that are to be implemented in smart city sub-area development and the latter are optional indicators that reflect the outcomes of such development (e.g., exploratory facets, innovation facets, etc.). The indicators listed in the guidance document only provide directional guidance. Furthermore, the index weights have not been defined and the said index system is merely a draft for comment instead of a finalized version. In late 2016, the three departments jointly published the "New Smart City Evaluation Index (2016)" (hereafter, "China Index 2016"), in which significant revisions to the guidance document are made. The China Index 2016, which comprises 8 primary indicators and 21 secondary indicators that are further divided into 54 sub-indicators, assigns weights to the various indicators, and the secondary-level sub-indicators are used for specific data collection. The indicators are mainly based on objective and quantitative data and avoid subjective scoring by experts as much as possible, as shown in Table 2 (National Development and Reform Commission, 2016). This index is the first national evaluation system for smart cities in China and thus is a primary guide for such development.

2.2. Critique of existing smart city evaluation systems

The smart city evaluation systems selected in this paper are typical and representative, including a global evaluation system (the ICF), an evaluation system for developed regions (the EU system), and a national evaluation system for China, the largest developing country. By studying these three smart city evaluation systems, this paper identifies some thought-provoking patterns.

With the exception of the ICF evaluation system, the other two systems place strong emphasis on the subjective experiences of citizens. In particular, in the Chinese system, the combined weight for the Public Services and Citizen Experience indicators is 57%, reflecting the core concept of people-oriented smart city development. On the other hand, all index systems include intelligent infrastructure indicators, which is the physical basis of smart city development. A smart city, at the very core, is a huge complex system that embodies the perfect integration of smart devices and intelligent humans. Furthermore, the indicators of all three evaluation systems cover a wide range of areas, including infrastructure, urban administration, public management and services, lifestyles, culture, the economy, regulations, the environment, and so on. There are also complex relationships and hierarchical structures among the indicators, which are in line with the characteristics of huge complex systems with numerous factors and complex hierarchical structures. An integrated qualitative-to-quantitative approach is required to critique the open and huge complex systems of smart cities (Qian et al., 1990), whereby the open, complicated, and intersecting nature of the systems is considered and various issues during development are handled in a holistic and dynamic manner.

However, the ICF and EU evaluation systems do not fully incorporate system-based concepts, placing higher emphasis on evaluating the ability of smart cities in solving practical issues. While the ICF focuses on solving issues related to the sustainability of urban competitiveness, the EU system focuses on solving green urban development issues. Although solving practical issues related to urban development is the direct objective of developing smart cities, evaluation systems that set out to solve practical issues are prone to losing sight of the forest for the trees, so to speak, and missing the essence of smart cities. In comparison, China Index 2016 incorporates more system-based concepts, covering governmental affairs, transportation, social security, medical services, education, employment, and other sectors under the primary indicator Public Services. To a certain extent it reflects the concept of classifying the various components of huge complex systems according to their hierarchical levels. However, such a vague hierarchical classification in turn blurs the assessment of smart city structural systems and thus lowers the scalability of the evaluation system. Smart cities are the cities of the future, and the future is hard to predict. Hence, current evaluation systems are incomplete and inconsistent to some extent.

In the same manner that 10 years ago it was inconceivable that mobile phones would completely revolutionize our lifestyles, the revolutionary changes of future cities are unpredictable and far beyond our current understanding. As such, the dynamic scalability of evaluation systems is crucial. The secondary indicators of the evaluation

Table 2
New smart cities evaluation index (2016).
Data source: City Evaluation Index (2016). Retrieved from http://www.sdpc.gov.cn/gzdt/201611/t20161128828092.html

Primary indicators	Secondary indicators
Public services (37%)	Government affairs (8%), transportation services (3%), social security services (3%), medical services (3%), education services (3%), employment services (3%), urban services (7%), assistance services (5%), E-commerce services (2%)
Accuracy of administration (9%)	Urban management (4%), public security (5%)
Livability (8%)	Smart Environmental Protection (4%), Green Energy Saving (4%)
Smart facilities (7%)	Broadband network facilities (4%), spatiotemporal information platform (3%)
Information resources (7%)	Open sharing (4%), development and utilization (3%)
Network security (8%)	Network security management (4%), system and data security (4%)
Revolutionary innovation (4%)	Institutional mechanisms (4%)
Citizen experience (20%)	Citizen experience survey (20%)
Optional indicators (10%)	Determined by the respective provinces, maximum of 3 indicators

Note: The weights of the indicators are indicated in parentheses.

system in the guidance document reflect the concept of scalability required in the index settings. However, this index system is just a draft for comment and has not been finalized. In the official version of the China Index 2016, which was released after the guidance document, self-selected indicators replace the expanded indicators. The scalability of self-selected indicators, which leave room for provinces to include their own area-specific indicators, are based on area-related differences instead of foresight and innovation. As such, overall, there are weaknesses in the existing index systems in terms of the clarity of hierarchical structures and scalability.

Scalability should be based on a core concept. The word “smart,” which was originally used to describe humans, is now used to define cities, implying that future cities will demonstrate agile behavior and acute thinking just like humans. In the China Index 2016, Smart Facilities are listed as a primary indicator, reflecting progress in the understanding of smart city systems. Smart Facilities, which are the core of what constitutes the open and huge complex system of a smart city, include intelligent household appliances, intelligent wearable devices, intelligent street lights, smart phones, intelligent cars, and other devices. Hence, as the foundation of a dynamic and lively smart city, this paper defines smart devices as smart cells. The creation and application of various types of smart cells, which will boost urban smart standards, are also the best entry point for a wide range of enterprises to participate in smart city development. Since enterprises are the most creative entities in smart city development, their widespread participation could be a constant force of innovation in such developments.

While existing evaluation systems incorporate system-based concepts, they tend to lean more towards a “vertical” approach that demarcates the smart city system, neglecting the “horizontal” relationships among the various system components. Hence, it is difficult to distinguish the structural relationships of the complex systems of smart cities. Studies on existing smart city evaluation systems tend to perform qualitative comparisons (Luo, 2017) or co-word analyses (Zhang, 2015) to assess existing evaluation systems. As it is difficult to cast aside the existing understanding of a smart city system framework in the conclusions of such studies, this results in study conclusions that lack innovation and foresight.

2.3. Urban self-organization theory

While organization refers to the ordered structure within a system or the formation of such an ordered structure, self-organization coordinates the operation of each system within the organization with default rules and spontaneously forms an ordered structure (Haken, 1983). The basic idea and theoretical core of the self-organization theoretical system are dissipative structure theory and synergetics. A dissipative structure is based on matter and energy exchanges with the environment. Life and cities have dissipative structure characteristics, whereby they are far from being in a state of equilibrium and are open systems with nonlinear mechanisms among different elements (Juval, 2012). Synergetics studies the synergistic mechanisms among the various factors of a system, which form the basis of the self-organization evolution process and are exactly what is required for coordination among urban systems. Dissipative structure theory, synergetics, catastrophe theory, and hypercycle theory form a self-organizing system, whereby these theories and urban science integrate to form urban self-organization theories.

Urban self-organization theories employ the views and methods of self-organization theories, studying theoretical systems in urban networks and their development processes from different aspects to form theories on dissipative cities (Prigogine and Stengers, 1984), synergetic cities (Haken and Fraser, 2000; Haken and Portugali, 1995), chaotic cities (Dendrinos and Sonis, 1990), fractal cities (Batty and Longley, 1994), sandpile cities (Bak et al., 1987), and cellular automata cities as well as FACS and IRN urban theories (refer to Table 3). The formation of the urban self-organization theories mentioned in the table prove the feasibility and scientific merit of using self-organization theories to study urban development issues.

While many urban self-organization models employ differential equations to perform tedious calculations, these sorts of calculations might not produce effective qualitative analysis results. Meanwhile, studies that have adopted these theories to analyze cities mainly focus on the spatial complexities of cities (Chen, 2003) not whole cities themselves.

3. Methodology

In this paper, we mainly adopt secondary qualitative data analyses, evaluating previous attempts at characterizing smart city development to identify the most robust aspects tested in previous work. The systems analyzed include the ICF evaluation system (Miller et al., 2010), the EU evaluation system (Giffinger et al., 2014), and the China evaluation system (National Development and Reform Commission, 2015; National Development and Reform Commission, 2016). Then, incorporating the results, we characterize smart cities as complex self-organizing systems, using self-organization theory for in-depth analyses.

Among urban self-organization theories, simple system analyses of CA-based network simulations may reveal more causal links (Chen, 2003). The CA is not determined by strictly defined physical equations or functions, but rather by a series of rules of model construction. Any model that satisfies these rules can be regarded as a CA model. Therefore, CA is a general term for a class of models, or a method framework (Zhang et al., 2014). The CA model, which includes two main factors (cells and rules), uses a set of simple local rules to generate complex global structures and behaviors. The dynamics of the model are generated by an iterative process in which the state of each cell is determined a new in every iteration by transformation rules. The rules are local and refer to the relations between the cell and its immediate neighbors. The goal is to see how, what, and in what circumstances

Table 3
Urban self-organization theories.
Data extracted from *Self-Organization and the City* (Juval, 2000).

Founders	Theoretical basis	Contribution	Theory essence
Prigogine and Stengers (1984)	Dissipative structure theory	Dissipative cities	The theory suggests that the order state of self-organizing systems is created due to dissipation, based on two innovative notions: (1) non-equilibrium and non-linearity under open environment conditions are the source of order; (2) self-organizing systems reach the order state after fluctuating.
Haken and Portugali (1995)	Synergetic theory	Synergetic cities	The theory explains how an order state is created and focuses on the interrelationships, interactions, synergy, macro structures, and overall behavior of all components of a system.
Dendrinos and Sonis (1990)	Chaos mathematics	Chaotic cities	There are two forms of chaos: local or microscopic chaos, and global, macroscopic, or deterministic chaos. Dissipative structure theory and synergetic theory focus on the former while Chaos theory focuses on the latter.
Batty and Longley (1994)	Fractal geometry	Fractal cities	The theory is based on two innovative notions: self-similarity and the fractal dimension. The complex geometries of urban space are formed through a rather simple iterative process via Mandelbrot's fractals.
Bak et al. (1987)	Self-organization critical model	Sandpile cities	Sandpile cities present a self-organized criticality and need no fine-tuning of external fields to take the system to the critical state. The sandpile has two incongruous features: the system is unstable in many different locations; nevertheless, the critical state is absolutely robust.
Neumann (1966)	Cellular automata model, cellular spatial model	Cellular cities, FACS and IRN cities	The cellular automata (CA) model including two main factors (cells and rules) uses a set of simple local rules to generate complex global structures and behaviors. FACS and IRN cities are based on cellular cities.

FACS, free agents on a cellular space; IRN, inter-representation networks.

local interrelations and interactions between cells lead to global structures, behaviors, and properties of the system as a whole (Juval, 2000). Hence, it is useful for analyzing the overall self-organizing framework of smart cities. Therefore, in this paper, we adopt the CA model to perform comparative analyses of smart city systems.

First, we construct an overall system framework of smart cities. We analogize a smart city to the human body, which is a perfectly spontaneous self-organizing system made up of cells. The comparative analyses adopted in this paper are not the qualitative type with support from statistical analyses but rather are simple qualitative analyses of smart cities and the human body, both of which are self-organizing systems.

Second, we explore the hierarchical relationships among various smart city components to demonstrate the main factors (the cells and rules of CA theory) involved in the evolution of smart cities basing on the CA model.

Third, we propose a scalable and distributed smart city evaluation system comprising three dimensions (smart cells, ICT, and developmental mechanisms), based on the CA model and mimicking the human body.

Finally, smart transportation systems are evaluated by mainly adopting qualitative analyses using our smart city framework.

4. Self-organizing system framework and an evaluation system for smart cities

4.1. Self-organizing system framework of smart cities

The human body is made up of nine systems, namely the locomotor, digestive, respiratory, urinary, reproductive, immune, circulatory, nervous, and endocrine systems. The smart city system is composed of systems such as transportation, environment, economy, security, energy, ICT, and institutional culture. A city's transportation system is similar to the locomotor system of the human body, connecting all corners of the city together. The environment of an urban area is similar to the urinary system in humans in that it promotes the "metabolism" of the city. An economic system is similar to the reproductive system of the human body, in that higher economic development standards breed new cities. A security system is similar to the immune system of the human body, reducing the probability of various urban disasters from occurring. The energy system of a city is similar to the circulatory system of the human body, supplying "nutrients" for the development of the city. Finally, ICT is equivalent to the nervous system of humans and institutional culture is equivalent to the endocrine system of the human body. These two systems play a key role in regulating, coordinating, and controlling the other systems, collaboratively enabling the overall functions of the city. On another note, as smart cities are open self-organizing systems, they need to exchange energy and information with the external world. This may be likened to the digestive and respiratory systems of the human body.

The human body is made up of cells; those with similar structures and functions form tissues, and multiple tissues with specific functions and structural characteristics form organs. Organs with related functions perform physiological functions, thereby forming a system.

Smart cells are the basic units of evolution of self-organization in smart cities. The variety of smart cells, the completeness of their functions and their penetration rates make up an inexhaustible driving force for the sustainable and healthy development of smart cities. In this paper, all types of smart devices are considered smart cells, which exchange information and gather, extract, and process data through distributed cloud platforms via ICT. Smart cells with similar functions interact with each other to form smart tissues. These smart tissues are the various micro-circulation elements in smart cities, such as micro-degradation, micro-purification, micro-energy, micro-upgrades, micro-transportation, micro-penetration, micro-green spaces, and micro-regulations, with each element being a functional component of smart cities (Qiu, 2016). The dynamism of smart cells and progress of ICT will lead to the development of new micro-circulation tissues, and distributed micro-circulation tissues are advantageous in terms of scalability and operational safety.

The various micro-circulation elements are interrelated and interactive. For example, certain innovations have promoted the birth of smart homes; these include innovations that use domestic waste to generate household power after undergoing micro-degradation, domestic water that is used for flushing after undergoing micro-purification, and potential energy generated from descending residential elevators used to charge electric vehicles. Meanwhile, widening the diameters of underground pipelines and creating micro-green spaces along streets and lanes could enable micro-penetration in a smart community, while micro-upgrades of micro-transportation and buildings could provide a foretaste of what a true smart city would look like. At the same time, urban micro-circulation elements form smart organs

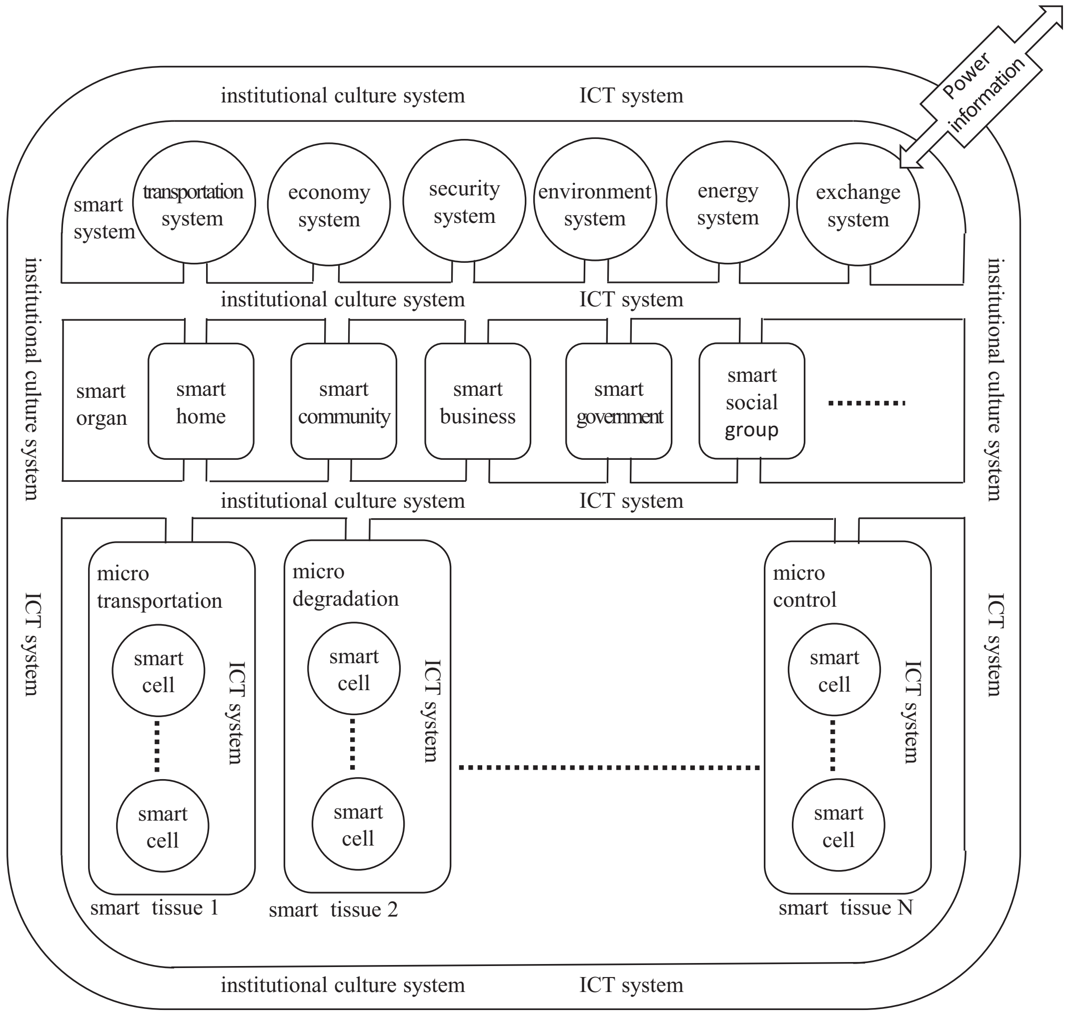


Fig. 1. Self-organizing system framework of a smart city.

with a complete range of functions, which include smart homes, smart communities, smart businesses, smart governments, smart social groups, and more.

Smart systems, which are made up of numerous functionally independent yet interrelated smart organs, include transportation, environment, security, energy, ICT, and economic and institutional culture systems. Driven by the two internal mechanisms of institutional culture and ICT, smart cells evolve from simple, crude phenomena into complex, refined entities during the formation of smart city systems. Such open systems would feature information and energy exchange with the external world to form a complete self-organizing system framework, as shown in Fig. 1.

4.2. The hierarchical relationships among various smart city components

Using self-organization theories to analyze smart cities in more detail demonstrates the hierarchical relationships among various smart city elements. As shown in Fig. 2, when facilitated by ICT and institutional culture, the various elements of smart cities are deeply integrated and connected on the same horizontal level, thereby enabling the "vertical evolution" of system functions. Smart cells form smart tissues, which form smart organs, which form smart systems, which ultimately form smart cities. The connections among elements within any given level and among different levels are crucial to the spontaneous evolution of the system, which abides by a simple-to-complex and low-to-high level order. In other words, smart cells represent the cell factor in the CA model, ICT and developmental mechanisms are the rules in the model, and the whole smart city system is created via a set of simple local rules.

4.3. A distributed smart city evaluation system

Basing on the CA model, for a smart city to mimic the spontaneous and harmonious patterns of the human body, there needs to be a wide and diverse range of smart cells with comprehensive functions and a set of rational and comprehensive "rules" about coordination. As such, three conditions need to be met to develop spontaneous coordination in smart cities: 1) the presence of huge numbers of smart cells with a comprehensive range of functions; 2) secure and smoothly functioning ICT; and 3) dynamic and effective developmental mechanisms. The first condition provides the "building blocks" upon which evolution can take place. The second condition ensures the smooth exchange and processing of information among the smart cells and other elements within the smart city. The third condition ensures that an entire smart city will be derived from higher-level smart elements (such as smart tissues, organs, and other systems) under the reasonable arrangement of game rules. The second and third conditions are two internal mechanisms that ensure system coordination, with the former being a technical condition and the latter being an institutional condition. Based on this analysis, this paper proposes a smart city evaluation system comprising three dimensions, namely, smart cells, ICT, and developmental mechanisms (as shown in Fig. 3). Through a set of general rules that clearly

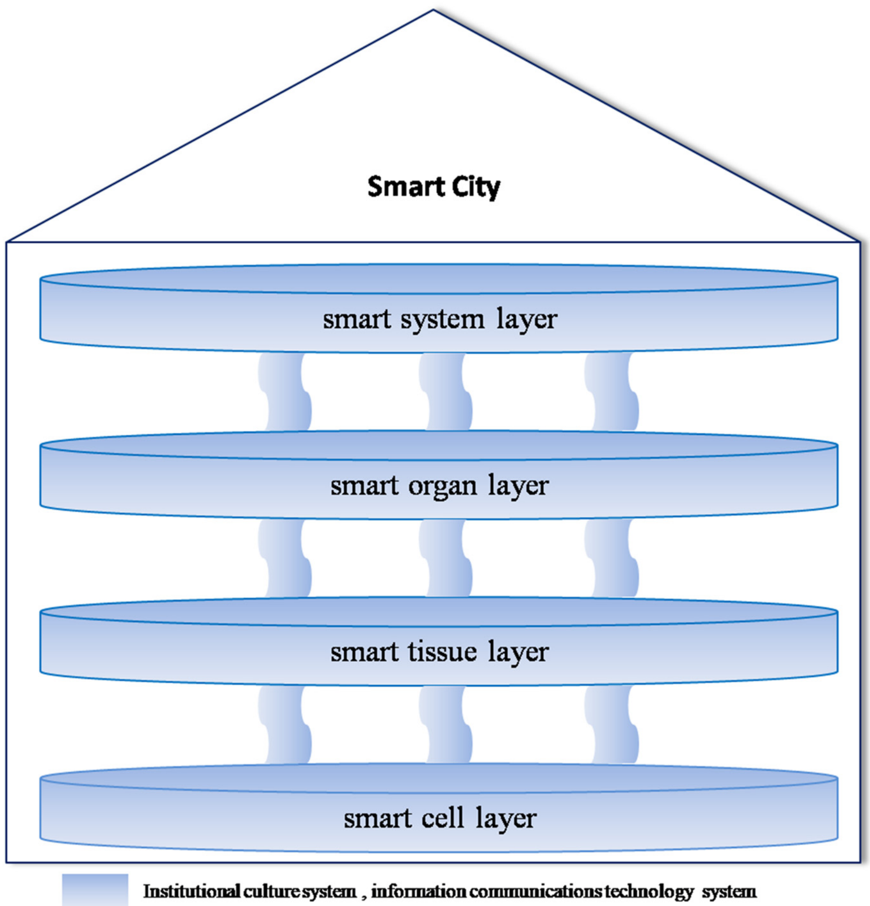
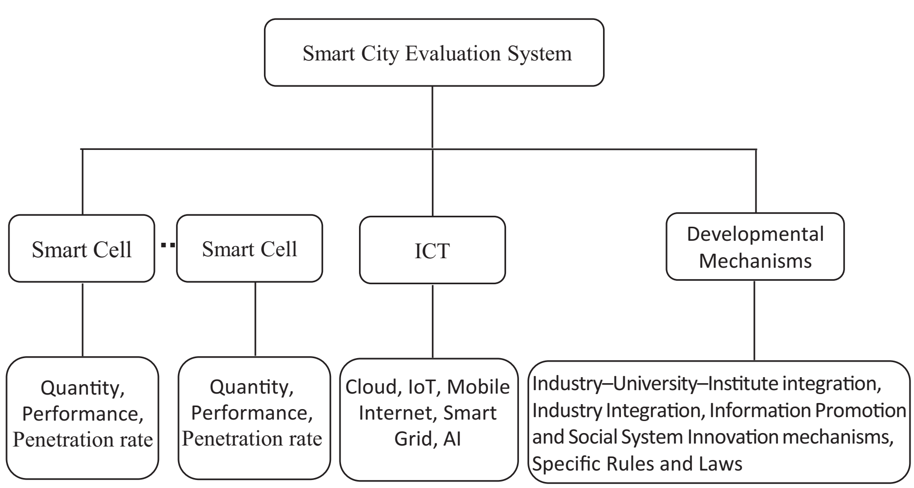


Fig. 2. The vertical and horizontal hierarchical relationships of smart city systems.

showcase the hierarchical relationships among the various smart city elements and their derivative trajectories, this evaluation system demonstrates the self-organization characteristics of a smart city system, which will ultimately provide a clearer understanding of the essence of smart cities.

While smart cells are the most basic units in the development of a smart city, whether a city has the requisite basic components of such a city depends on the quantity, performance, and penetration rate of each smart cell. At present, the known smart cell morphology is primarily made up of smart devices with sensitive and accurate sensor functions, correct "thinking" and "judging" functions, and well-functioning executive functions. However, this paper uses smart cells instead of smart devices as the evaluation dimension of smart cities, mainly because smart cells embody the basic unit characteristics of a smart city, and such a concept is scalable. Hence, this strengthens the foresight, dynamism, and scalability of the evaluation system.

ICT is the convergence of information technology and communications technology. Information technology focuses on the coding or



ICT, information communications technology; IoT, internet of things; AI, artificial intelligence

Fig. 3. A smart city evaluation system based on self-organizing systems.

Table 4
Three dimensions of a self-organizing smart transportation system.

Dimensions	Summary
Smart cells	Smart cars, unmanned aerial vehicles, smart infrastructure and devices, and smart base stations
ICT	IoT, big data, cloud computing, mobile internet, artificial intelligence
Developmental mechanisms	Smart traffic rules, operation mechanism of the sharing economy

decoding of information, as well as the calculation and processing of information. Communications technology, on the other hand, focuses on the transmission of information (Lin, 2010). The construction of a smart city requires ICT support. Currently, popular ICT technologies applied to the construction of a smart city include cloud, Internet of Things (IoT), mobile internet, smart grid, and AI technologies. The development standards of these technologies influence the connections among the various smart city elements and determine the formation of the self-organizing system.

The developmental mechanisms of smart cities, such as the industry–university–institute integration, industry integration, information promotion, and social system innovation mechanisms, primarily coordinate operations among various higher-level elements of a smart city framework (smart tissues, smart organs, and smart systems). While the connections among smart cells on the lower-level structure of a smart city system require ICT systems, developmental mechanisms are also sometimes required to enable such connections. Such developmental mechanisms primarily comprise specific rules and laws such as road traffic rules for smart vehicles.

A distributed smart city evaluation system based on self-organization theory helps to crystallize the properties and structural characteristics of smart cities. A smart city evaluation system comprising the three dimensions of smart cells, ICT, and developmental mechanisms is able to measure the overall development standard of a smart city while also separately evaluating smart city subsystems such as transportation, security, and the environment, so as to measure the ability of a smart city in resolving a specific issue related to urban development.

5. A case study: smart transportation systems

In the current transitional period of urban governance methods, distributed governance and self-organizing evolution will become imperative forces to promote the development of a smart city. The centralized approach to governance should be replaced with a distributed approach while the single-direction approach should be replaced with a circular approach. This will help bring about urban micro-circulation starting from a small and decentralized approach, thereby transforming the urban governance model. While the current developmental phase of smart cities involves the enrichment and improvement of smart cells and the formation of smart tissues, the developmental focus should be on research and development (R&D), production, and application of smart devices as well as the creation of urban micro-circulation processes. Thus, separate evaluations of certain smart city systems as they exist today would be of significant practical value in terms of guiding the sustainable and healthy development of smart cities. For example, when studying smart transportation systems, focus could be given to smart cells associated with the current status of smart transportation devices, the development and use of transportation and communication technologies, and smart urban traffic planning.

Traffic congestion is an urban issue that increases traveling time and costs, worsens air pollution, consumes high levels of energy, and leads to traffic accidents. According to an INRIX report, traffic congestion in 2017 cost American drivers US$350 billion, with an average loss of US $1445 per driver. In China, the pollution from motor vehicle emissions has become a key contributor to air pollution. According to the China Vehicle Emission Control 2017 Annual Report released by the Ministry of Environmental Protection of the People's Republic of China, the pollutants emitted by motor vehicles nationwide amount to 44 million tons. Road-widening efforts cannot keep up with the increasing number of cars on roads, and road space rationing measures based on license plate numbers only serve to provide symptomatic relief while also giving rise to public dissatisfaction and various social issues. Increasing the availability and use of public transportation is a generally recognized method to alleviate traffic congestion, and the construction of smart transportation devices is the ultimate solution to solving traffic congestion.

5.1. Self-organization framework of smart transportation systems

Smart transportation is changing urban commuting methods. A traffic-management system that predicts densely populated roads based on present and past traffic congestion and suggests alternate paths for a given starting point and destination has been proposed (Sekar et al., 2017) while an interactive visual analytics platform for the management of smart transportation systems has been suggested (Kalamaras et al., 2017). These solutions, which are essentially reconstructions and upgrades of conventional traffic models, are highly beneficial in solving traffic congestion issues. For this paper, a literature review of smart transportation systems within a self-organizing smart city framework was conducted. In line with this paper's thesis, a smart transportation system would require a rich range of smart cells. Based on the current understanding of smart transportation systems, the smart cells should at least include smart cars, unmanned aerial vehicles, smart infrastructure and devices, and smart base stations. Supported by ICT and enabled by various developmental mechanisms, these smart cells form a smart transportation system as summarized in Table 4.

As shown in Fig. 4, the smart cells of a smart transportation system are divided into those with and without conveyance capacities. Smart cars and unmanned aerial vehicles fall under the former category while smart infrastructure devices and smart base stations fall under the latter category. Smart cells with ICT capacities could form a dynamic self-organizing network. Smart cells with conveyance capacities are mobile nodes of the self-organizing network, while those with non-conveyance capacities are fixed nodes. The mobile nodes constantly establish automatic networks with other mobile nodes and fixed nodes within the communication range, forming a micro-transportation system with the capacity to organize autonomously. A micro-transportation system is a distributed system, which is a smart tissue of a smart city. Under the existing ICT standards, ICT tasks of smart tissues that involve the external world are primarily facilitated by fixed nodes to ensure the stability of information and communication. Following the development of ICT and improvements in the “intelligence” of smart cells, the differentiation in terms of the functions of mobile nodes and fixed nodes will be diminished, whereby mobile nodes may also be able to connect and communicate with the external world in a stable manner. When that happens, the smart attributes of all smart cells within a smart transportation system shall be homogenized, and the differences among them will only be in whether they possess conveyance capacities (mobile) or non-conveyance capacities (fixed).

The ICT of a smart transportation system primarily comprises IoT, big data, cloud computing, mobile internet, and AI. The benefits of applying big data techniques over data originating from IoT-based devices deployed in smart cities are becoming apparent (Hashem et al., 2016; Moreno et al., 2017). Technologies such as big data, cloud computing, and IoT have been incorporated into transportation systems, and such technologies would ensure the operation of smart transportation systems. Smart self-driving vehicles are definitely mobile smart cells of smart transportation systems of the future, and stable and reliable V2X self-organizing network technologies are required to ensure the safe operation of such vehicles. Meanwhile, the application of AI technology is also key to realizing a smart transportation system of

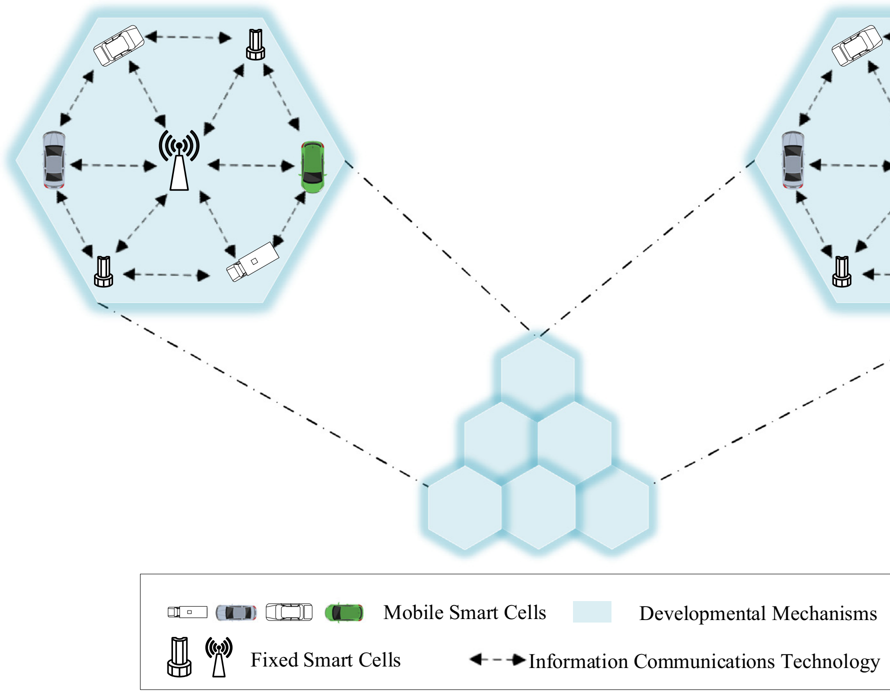


Fig. 4. Smart transportation system self-organization framework.

the future. This paper classifies the way in which AI technology replaces manpower in terms of smart transportation systems into three categories: 1) AI technology that replaces physical functions to ensure the autonomous driving of cars under unmanned conditions; 2) AI technology that replaces the human consciousness of abiding by traffic laws to ensure that cars are driven according to the stipulated traffic rules; and 3) AI technology that replaces the human brain in revising traffic rules to optimize the operating efficiency of traffic systems through revision of traffic rules based on accumulated big data information and cloud-computing findings. The third aspect of AI technology involves the traffic rules aspect of developmental mechanisms. According to current understanding, human intelligence is primarily required to innovate and develop the operating mechanisms of an economic society.

Uber and Didi Chuxing are the leading one-stop commuting platforms in the world. In big data reports on smart commuting in China released by the Didi Media Research Institute in recent years, "smart commuting" refers to rides booked online. This shows that the sharing economy model will be a significant economic and social backdrop for the operations of smart transportation systems. Before traveling, a passenger may put in an online order for a shared unmanned vehicle through a mobile application or some other smart device, whereby the nearest fully charged vehicle will arrive at the designated location within the shortest time possible to pick up the passenger and take him or her to the destination. If the distance of the journey is too long and the battery life of one vehicle is insufficient to complete the entire journey, the online vehicle booking platform will assign another fully charged vehicle to replace the first vehicle at a suitable point in the journey, thereby enabling the passenger to continue and complete the journey. The vehicle with the depleted battery will then go to the nearest charging station and be deployed again after the charging is completed. This will not only solve the problem of urban commuting, but also solve the problem of insufficient battery life and charging difficulties of electric vehicles. When shared unmanned vehicles have become mature urban commuting solutions, there will be significant changes in the ownership of existing vehicles, whereby vehicles will no longer be differentiated as private or public vehicles and private vehicles will be eliminated. Cars will only be differentiated as smart person-carrying vehicles and smart cargo-carrying vehicles, whereby the system will automatically assign different types of smart vehicles based on user requirements. For a single-passenger trip, the system will assign a small-sized person-carrying vehicle (hereafter, an unmanned capsule vehicle). For a multiple-passenger trip, the system will assign a large one, or based on passenger requirements, assign multiple unmanned capsule vehicles, which could be connected to each other like the cars of a train to form a capsule vehicle group. When this takes place, people no longer have to top-up energy resources for their vehicles, send their vehicles for maintenance, or worry about parking issues. Instead, they could simply order a suitable smart car on a platform based on their needs, thereby cutting down personal commuting costs. Meanwhile, the elimination of private vehicles will greatly alleviate traffic congestion issues, thereby bringing about a range of social benefits such as improvement in the energy utilization rate within the society and environmental pollution issues. The evolutionary trend of smart transportation systems requires the support of a range of developmental mechanisms such as sharing economy systems and unmanned vehicle traffic rules.

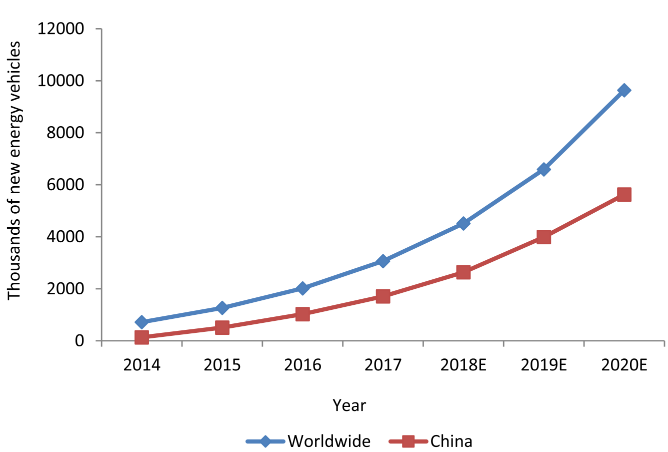
The "intelligence" of a vehicle is mainly confined to the different levels of unmanned driving enabled by the use of smart devices such as advanced sensors (radar, cameras, etc.), controllers, and actuators that enable information exchange among drivers, vehicles, and roads through vehicle-mounted sensor systems and information terminals. These devices provide vehicles with the environmental awareness to automatically assess driving safety and risks, allowing them to arrive at the desired destination. Intelligent vehicles, sensors, controllers, and actuators are all smart cells that enable the ICT-supported generation and exchange of information for the purpose of unmanned driving. In fact, intelligent vehicles could go beyond being just unmanned vehicles; they could also become smart mobile spaces when installed with more smart applications. Currently, it is conceivable that these smart mobile spaces could offer all the features of a smart phone. For example, when you are driving past a restaurant you frequently patronize, the intelligent program in the vehicle will automatically enquire whether you would like to disembark for a meal or have your regular takeaway order delivered to your home. The implementation of these functions requires ICT support, big data, and cloud-computing technologies. It is not far-fetched to have a smart transportation system reconstructed from core smart cells of unmanned vehicles that have been installed with various smart applications. With ICT support, such vehicles will be spontaneously realized via legal systems that address smart road network planning, smart traffic regulations, operating mechanisms of the sharing economy, and ban orders on fuel-operated vehicles.

5.2. Evaluation of the current state of smart transportation systems in China

In China, JD.com has begun a trial implementation of unmanned vehicles, and the first unmanned bus trial was launched in Shenzhen in December 2017. Following the release of the “Guidance Document and Management Regulations Concerning the Acceleration of Relevant Tasks Pertaining to the Road Tests for Self-Driving Vehicles” by the Beijing administration and the selection of the first driverless vehicle pilot road at Yizhuang in Daxing District, the use of unmanned vehicles seems imminent. In the following section, smart vehicles as smart cells are used as an entry point to analyze the current state of smart transportation systems in China.

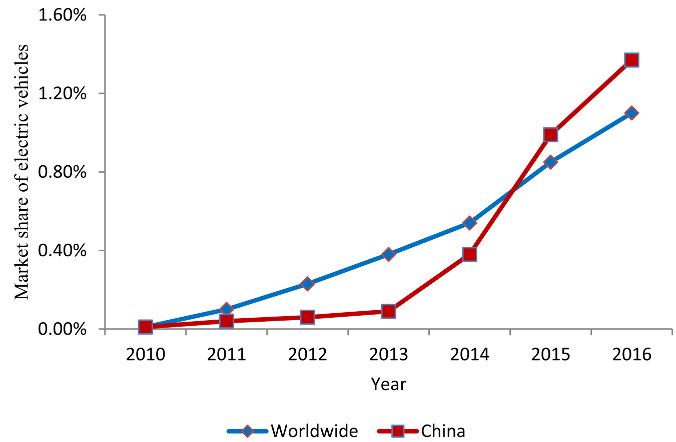
5.2.1. Smart cells

Although smart vehicles have not yet been deployed on a large scale, it is easier for electric vehicles to fulfill smart development objectives as compared to their traditional vehicle counterparts. As such, the quantities, performances, and penetration rates of electric vehicles could be viewed as the basis for the development of smart vehicles. In terms of quantity, ownership of electric vehicles is gradually increasing, and is expected to reach 1 million globally and 0.6 million in China by 2020 (as shown in Fig. 5). In terms of performance, while the recharging and mileage issues of electric vehicles have generally been solved and quick-charging issues are in the midst of being addressed, these are just improvements to conveyance capacities that will only serve to put electric vehicles on par with traditional fuel-operated vehicles. Improvements to the “intelligence” of electric vehicles should be the developmental direction of the future, and these improvements are also required by a smart transportation system. Based on the American classification standards, unmanned vehicle technologies are divided into six phases. The present-day unmanned vehicles are generally in the third and fourth phases, indicating that there is still a long way to go before completely unmanned vehicles are a reality. Meanwhile, unmanned vehicles are still not equal to smart cars. On top of their unmanned driving functions, smart cars need to be installed with more smart attributes that enable connections and communication with the external world. In terms of penetration, the global market share of electric vehicles grew from 0.1% to 1.1% between 2010 and 2016, while the market share in China increased from 0.1% to 1.37% and exceeded the world average around 2015 (as shown in Fig. 6).



Data source: Wind information database. E, estimated values.

Fig. 5. Ownership trends of electric vehicles worldwide and in China.



Data source: International Energy Agency.

Fig. 6. The market share of electric vehicles out of the total car market worldwide and in China.

However, the penetration rate is still very low.

5.2.2. Information and communication technology

Big data, cloud computing, IoT, AI, and mobile communications technologies are important ICT technologies in the operation of smart transportation systems. IoT technology in particular is a key player, especially wireless self-organizing network technology. Under the limitations of the current standards of wireless self-organizing networks, most of the time a well-defined path from a consumer to the provider does not exist due to intermittent connectivity and mobility (Wahid et al., 2017). Self-driving smart vehicles are also the mobile smart cells of a smart transportation system. These cells need to continually form a dynamic network with surrounding smart cells, thereby having rather high ICT requirements in terms of signal strength and stability. Compared to wireless self-organizing networks, the development standards of big data, cloud computing, IoT, and other technologies (such as RFID, GPS, etc.) are higher. Big data and cloud-computing technologies are already widely used in smart cities, and are highly applicable for weather forecasts and virtual reality (Chang, 2015; Chang, 2017). AI technology, which is perhaps most vividly demonstrated in Go, a strategy board game invented in ancient China (known as “Weiqi” in Chinese), has already been incorporated into smart transportation systems. In its 2018 Intelligent Transportation Summit, Didi unveiled its “Traffic Brain” system, which has been embedded with AI technology. The product, which is a smart system that employs cloud computing, AI technology, traffic big data, and traffic engineering, has been put to use in more than 20 Chinese cities. Featuring smart traffic engineering such as smart traffic direction screens and smart semaphores, the system optimizes urban traffic management and relieves traffic congestion. In February 2018, the Malaysia Digital Economy Corporation and Kuala Lumpur City Hall announced that they would bring in the Ali Cloud ET City Brain. Under this initiative, AI would first be applied at 281 road intersections in Kuala Lumpur, the capital city of Malaysia, whereby traffic congestion in the city would be alleviated through dynamic regulations of traffic lights, traffic accident detection, and priority lanes for emergency vehicles.

Overall, the various technologies currently used in smart transportation systems are reconstructions and upgrades of conventional traffic systems. This is the initial stage, as smart transportation systems evolve to address traffic congestion issues, and there is still a long way to go before truly smart transportation systems are a reality.

5.2.3. Developmental mechanisms

On September 12, 2017, the U.S. Federal Government officially passed the first unmanned vehicle bill. Prior to this, there were already more than 22 states that passed related laws on unmanned vehicles. While China is not far behind the United States in terms of AI technology, it is obviously trailing behind in terms of law making, with only Beijing issuing the first regulations on unmanned vehicles in China by the end of 2017. As mentioned in the previous section, the sharing economy model will be a significant economic and social backdrop for smart transportation systems. The troubles currently faced by the bike-sharing market in China also reflect the weak mechanisms that safeguard the operations of a sharing economy. Because smart vehicles are the core smart cells of smart transportation systems, the developmental pace of smart vehicles will determine the development process of smart transportation systems. As the Chinese government places high emphasis on this matter, the Development and Reform Commission issued the "Smart Vehicle Innovation Development Strategy (Draft for Comment)" on January 6, 2018, which proposes a three-step strategy to become a strong nation of smart vehicles by the year 2035.

Overall, the formulation of various developmental mechanisms that ensure the operation of smart transportation systems are still in the preliminary stage and are highly incomplete.

5.3. Discussion

From a development perspective of smart transportation systems, there is still room for breakthroughs in key technologies of smart transportation systems despite their rapid development. For example, the types, performances, and penetration rates of smart cells could still be greatly improved. Meanwhile, although the developmental mechanisms required for the evolution of the system are in the preliminary stage, they are far from perfect. As such, we are only on our way to accessing smart transportation systems and still have a long way to go before experiencing true smart transportation systems as a reality. Through the evolutionary process of self-organizing smart city systems, humans should take up the responsibilities of formulating innovative developmental mechanisms that cannot be performed by AI. The role of humans is primarily demonstrated in the third dimension of a distributed smart city evaluation system, i.e., the developmental mechanisms dimension. Furthermore, the formulation of developmental mechanisms should be done in accordance with the evolutionary self-organization patterns of smart cities, so as to make up for the weaknesses of the spontaneous evolution process of smart cities and employ an external catalysis effect. For the administrations of more than 500 cities in China that have commenced smart city development, these findings should provide food for thought that humans should neither be planners and controllers nor bystanders in smart city development. Instead, urban administrations should focus on promoting industrial policies and the industry–university–institute integration mechanism aspects of smart device and ICT development while pushing for the formulation of innovative developmental mechanisms for unmanned vehicle laws and the sharing economy. Wanton development and obtaining central government subsidies with an aim of establishing smart cities are to be avoided, while the third dimension of the distributed smart city evaluation system should be used as a reference in the establishment of truly smart cities.

6. Conclusion

This paper proposes a smart city evaluation system that reflects the self-organization characteristics of smart cities while integrating distributed governance concepts to aid understanding of the structural characteristics and nature of smart cities, which are huge complex systems. A distributed smart city evaluation system framework based on self-organization theory is a useful guide for correctly developing smart cities in a sustainable and healthy manner.

Many previous papers on smart cities do not employ self-organization theory, and the few that do only discuss the structure of the smart city system itself. To the best of our knowledge, no previous paper has applied the theory to the evaluation system of a smart city. This paper first defines smart devices as smart cells to compare the various urban systems to the human body while discussing how smart cells form the smart city self-organizing system through mechanisms such as ICT and institutional culture. Based on these factors, a smart city evaluation system that reflects the self-organization characteristics of smart cities while integrating distributed governance concepts is proposed to aid understanding of the structural characteristics and nature of smart cities, which are huge complex systems. Then, smart transportation systems are used as a case study to trigger thoughts on smart city development; the current state of smart transportation systems in China is also discussed in detail. A distributed smart city evaluation system framework based on self-organization theory not only promotes urban self-organization theory, but is also a useful guide for correctly developing smart cities in a sustainable and healthy manner. Issues such as overdevelopment and wanton development in China will gradually be solved by implementing well-designed smart city systems.

This study is not without limitations. Integrated quantitative and qualitative research methods are effective for solving issues in huge complex systems (Qian et al., 1990). Among the three dimensions of the distributed smart city evaluation system mentioned in this paper, smart cells are rather quantifiable, although truly quantifying all smart cells in the system would be highly difficult. Meanwhile, qualitative analysis is more suitable for the dimensions of ICT and developmental mechanisms. While the self-organizing smart city system framework and distributed evaluation system could help us understand the essence of smart cities, there are still weaknesses in using a distributed evaluation system to measure the development standards of smart cities. This will be a research direction for future studies. Even more, in our opinion, smart cities are the cities of the future and they will be completely intelligent in all aspects. At present, the construction of smart cities is still in the process of solving specific problems in urban development. Because traffic congestion is the most serious problem to address in smart city development, we use a smart transportation system as a case study. However, a smart transportation system is not exactly analogous to a smart city system. Hence, this is also a limitation of this paper. We will evaluate a Chinese city using the distributed evaluation system in a future study.

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